Viewgraphs from May 12, 2005 meeting in order of presentation

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freedomCAR & vehicle technologies program

21st Century Truck Partnership

May 12, 2005

Kenneth C. Howden
Office of FreedomCAR and Vehicle Technologies (FCVT)
Energy Efficiency and Renewable Energy
U.S. Department of Energy

21ST CENTURY TRUCK PARTNERSHIP

21CTP

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Outline of Presentation

- Vision for the Partnership
- Organization of Partnership
- Activities of Partnership
- R&D Goals of 21CTP
- DOE 21CT Research Priorities

21ST CENTURY TRUCK PARTNERSHIP

21st Century Truck Partnership

"The progress we are making in heavy truck technology under the 21st Century Truck Partnership will provide the United States with significant efficiency and safety benefits, and cleaner air, while helping to maintain America's international competitiveness in this key industry sector."

Energy Secretary Bodman speaks at the 21st Century Truck Partnership event at SAE Government Industry Meeting in Washington, D.C. on May 10, 2005

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21CTP Addresses National Imperatives

Transportation in America supports:

- the *growth of our nation's economy* both nationally and globally,
- the country's goal of *energy security.*
- an *agile, well-equipped, efficient military force* capable of rapid deployment and sustainment anywhere in the world.

Transportation in our country is *clean, safe, secure, and sustainable.*

Our nation's transportation system is compatible with a *dedicated concern for the environment.*

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21st Century Truck: A Government-Industry Partnership

DOE / EE
FreedomCAR and Vehicle Technologies

DOD / Army
TACOM NAC
Military Vehicle R&D

DOT / RSPA
Intelligent Vehicle and Highway Safety R&D

EPA
Vehicle Emissions Regulations

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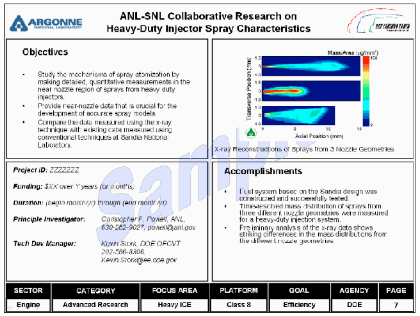
Partnership Coordination

- "Face to face" meetings
  - Full Group (6 per annum)
  - Sectors – Engine, Hybrid, Truck OEM (2 each per annum)
- Biweekly teleconferences
  - Government
  - Industry
  - Combined government/industry
- Focus area white papers (five)
- Login protected web-site
- Project inventory (searchable database)

Additional Resources (in development)

- Non-partner collaboration plan
- Book of project one-pagers
- Technical validation plan
- Public web-site



ARGONNE NATIONAL LABORATORY

ANL-SNL Collaborative Research on Heavy-Duty Injector Spray Characteristics

Objectives

- Study the mechanisms of spray atomization by making detailed, quantitative measurements in the near nozzle region of sprays from heavy duty injectors.
- Provide near-nozzle data that is crucial for the development of accurate spray models.
- Compare the data measured using the x-ray technique with existing data measured using conventional techniques at Sandia National Laboratory.

X-ray Reconstructions of Sprays from 3 Nozzle Geometries

Project ID: *ZZZZZZZ*

Funding: *$XX over Y years (or months)*

Duration: *(begin month/yr) through (end month/yr)*

Principle Investigator: *Christopher F. Powell, ANL, 630-252-9027, powell@anl.gov*

Tech Dev Manager: *Kevin Stork, DOE OFCVT 202-586-8306, Kevin.Stork@ee.doe.gov*

Accomplishments

- Fuel system based on the Sandia design was constructed and successfully tested.
- Time-resolved mass distribution of sprays from three different nozzle geometries were measured for a heavy-duty injection system.
- Preliminary analysis of the x-ray data shows striking differences in the mass distributions from the different nozzle geometries.

SECTOR	CATEGORY	FOCUS AREA	PLATFORM	GOAL	AGENCY	PAGE
Engine	Advanced Research	Heavy ICE	Class 8	Efficiency	DOE	7

Partnership RD^3 Focus Areas

Technology goals focus on five key areas for heavy duty vehicles

- Engine Systems
- Heavy-Duty Hybrids
- Parasitic Losses
- Idle Reduction
- Safety

Support Research, Development and Demonstration

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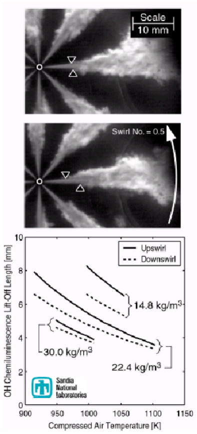
21CTP Engine Systems Goals

Improve Efficiency of Engine Systems

- Improve Class 7- 8 brake thermal efficiency to 50% by 2010
- Research and develop technology to achieve 55% efficient prototype by 2012
- Explore new diesel fuel specs using renewables and non-petroleum-based fuels to displace 5% of petroleum by 2010



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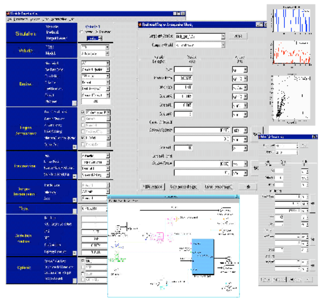
21CTP Heavy Hybrid Goals

Reduce Heavy Hybrid Component Costs to Promote Market Penetration

- Develop new generation of drive units with higher specific power, lower cost and durability matching service life of vehicle (15 yr design life) for under $50/kW by 2012
- Develop energy storage systems with 15 yr. design life, that prioritize higher power vs. higher energy, costing under $25/kW by 2012
- Develop and demonstrate 2007 emissions-compliant heavy hybrids with 60% fuel economy improvement on an urban driving cycle

Rapid Automotive Powertrain Simulator - Truck Simulation Model (RAPTOR-TSM) was used for performance and fuel economy analysis



UNITED STATES ARMY NAC NATIONAL AUTOMOTIVE CENTER

SwRI

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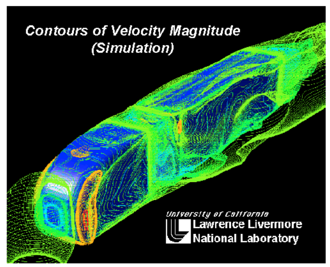
21CTP Goals for Mitigating Parasitic Losses

Reduce Parasitic Losses to Regain Horsepower in Class 8 Trucks

- Demonstrate 20% reduction in heavy vehicle drag coefficient by 2012
- Demonstrate 50% reduction in essential aux. power loads on heavy vehicle by 2012
- Validate 15-20% weight reduction in Class 8 tractor-trailer through materials optimization



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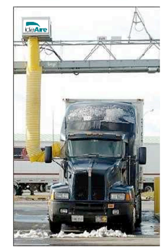
21CTP Idle Reduction Goals

Reduce Idling Fuel Use and Emissions by 85%

- Demonstrate and demonstrate advanced 5 kW auxiliary power units (APUs) that are quiet, weigh <200 lb, consume <0.25 gal/h diesel fuel @ full load and meet Tier 2 Bin 10 emissions for under $200/kW by 2007
- Develop and demonstrate 5-30 kW *fuel cell* APUs that use multiple fuels and operate at > 35% efficiency for under $400/kW by 2012
- Develop new codes and standards for electrification of trucks and truck stops



SmartWay Transport Partner
Getting There With Cleaner Air

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21CTP Safety Goals

Contribute to Reducing Truck-related Fatalities by 50% (vs.1996) through Safer Trucks

- Improve crashworthiness at highway speeds through better materials and vehicle design
- Improve crash avoidance for trucks through better braking, rollover stability and visibility

Static tilt table test to assess rollover stability

21st Century Truck

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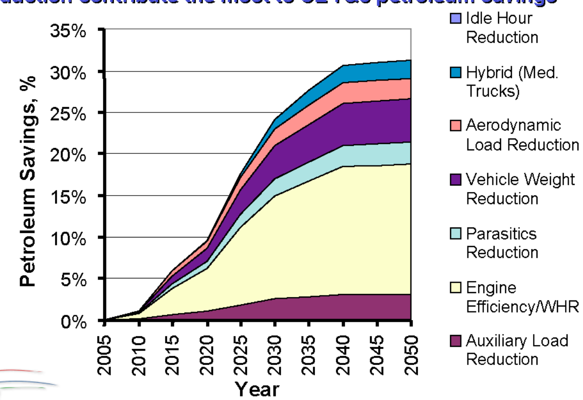
Petroleum Savings by Technology

Engine Efficiency/Waste Heat Reduction and Vehicle Weight Reduction contribute the most to CL 7&8 petroleum savings



21st Century Truck

GPRA 06 FCVT Heavy Vehicle Benefits, Preliminary Results, TA Engineering

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Merit/Peer Review Schedule

				2005												2006					
	Merit Review Topic	White Paper	Gov. Agency	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	June
Engine	Engine, Combustion & Emission Control	Engine Systems	DOE, EPA, DOD																		External Peer Review
Engine	Fuels Technology	Engine Systems																			
Engine	Propulsion Materials	Engine Systems	DOE																		
Hybrid	Subsystem Integration and Development, Energy Storage, Advanced Power Electronics	Heavy-Duty Hybrids	DOE, EPA, DOD																		
Truck OEM	Vehicle Systems (Aerodynamic Drag, Rolling Resistance, Thermal Management, Friction, Wear)	Parasitic Losses	DOE																		
Truck OEM	High-Strength Weight Reduction Materials	Parasitic Losses	DOE																		
Truck OEM	Idle Reduction (Automatic Start/Stop Systems, Auxiliary Power Units, Truck Stop Electrification)	Idle Reduction	EPA, DOE																		
Truck OEM	Crash Avoidance, Crash Worthiness	Safety	DOT																		
Truck OEM	Advanced Systems & ITS	Safety	DOT																		

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Partnership Accomplishments

- Defined 21CTP Vision
- Completed Project Inventory
- Established Technology Focus Teams
- Drafted "White Papers" in each Technical Area
- Established Goals for each Technical Area
- Established 21CTP website to disseminate information and share data

Assistant Secretary David Garman announcing 21CT Goals at SAE Government-Industry Meeting May 2003

Exhibit at EPA/DOE Idle Reduction Conference, May 2004

- Co-sponsored Idle Reduction Conference with EPA, May 2004
- Organized Heavy Duty Vehicle Display at 2004 and 2005 SAE Government - Industry Meetings

21ST CENTURY TRUCK PARTNERSHIP


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21ST Century Truck
– Moving Forward
21st Century Truck Heavy Duty Vehicle Display, SAE Government/Industry Meeting, May 2005, Washington, DC
21ST CENTURY TRUCK

Truck Manufacturers Association Aerodynamic Drag Project with DOE/NETL

Mike Laughlin
New West Technologies, LLC
-for-
Robert Clarke, President
Truck Manufacturers Association

Overview

- TMA Description and Management
- Project Partners
- Activities in this Project
- Contacts for More Information

2

TMA Overview

- TMA represents manufacturers of Class 6-8 trucks in North America
- TMA offers "one-stop shop" access to key HD manufacturers
- TMA role is to foster information sharing in this project to the extent possible while protecting intellectual property interests
  - Maximize benefits of project activities to all parties

3

Project Partners

- Project includes four key truck OEMs who will be doing the aerodynamic research
  - Freightliner LLC
  - International Truck and Engine Corporation
  - Mack Trucks, Inc.
  - Volvo Trucks North America, Inc.

4

Project Overview

TMA® TRUCK MANUFACTURERS ASSOCIATION

- Partners are researching effects on Class 8 truck aerodynamics of these areas:
  - Mirror design
  - Aerodynamic treatments of tractor trailer gap, trailer side, and trailer wake
  - Trailer aerodynamics, trailer gap enclosure, and trailer gap flow control
  - Vehicle underside design and management of tractor-trailer air flows
- Each participating manufacturer is taking a lead role in one of these four areas
- Results shared through normalized fuel economy and/or drag coefficient improvements on percentage basis
- Project duration of two years (October 2004-September 2006

5

Mirror Design

TMA® TRUCK MANUFACTURERS ASSOCIATION

- Research effects of mirror design and configuration on aerodynamic performance through:
  - Computational fluid dynamics
  - Wind tunnel testing of full-scale trucks (drag measurements and flow visualization)

6

Trailer Gap/Side/Wake

- Address tractor trailer gap closure, trailer side enclosure, and trailer wake
  - Scale model wind tunnel testing of all promising concepts
  - Full-scale testing of best concepts with on-road vehicle testing in field

7

Trailer Aerodynamics/Gap Enclosure/Gap Flow Control

- Examine trailer-specific aerodynamic aids; gap enclosure systems; and gap flow control methods
  - Focus on road testing of concepts to bridge gap between CFD modeling and full-scale vehicle operation
  - Work with CFD modelers to characterize effects of aero concepts
  - Use SAE fuel economy testing to determine overall effects

8

Vehicle Underside/Management of Tractor-Trailer Air Flows

TMA® TRUCK MANUFACTURERS ASSOCIATION

- Examine systems that manage vehicle underside air flow and systems that direct air flows in the tractor trailer gap
  - Main focus is underside air flow
  - Characterize effects through real-time fuel economy data on test loop

9

TMA Track Test Day

TMA® TRUCK MANUFACTURERS ASSOCIATION

- Vehicles from this project will be displayed at a test track at end of project
- Discuss and demonstrate project successes
- Track location to be determined

10

Current Progress

- Contractual negotiations virtually complete
- Second draft of test plan describing overall research is being reviewed at NETL
- Project partners commencing research efforts

11

Questions or Comments

- Overall project lead for TMA is
  - Robert M. Clarke, President (202-638-7825, robertmclarke@earthlink.net

12

Achievements

Heavy Vehicle Drag Reduction Program

Kambiz Salari

Heavy Vehicle Aerodynamic Drag Working Group Meeting

May 12, 2005

This work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under Contract No. W-7405-ENG-48.

Acknowledgements

Rose McCallen, Jason Ortega, Craig Eastwood, John Paschkewitz, Paul Castellucci

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Dave Whitfield, Ramesh Pankajakshan

Anthony Leonard, Mike Rubel

James Ross, Bruce Storms

Robert Englar

David Pointer

Collaborator: Kevin Cooper, Jason Leuschen

Goal: Reduce heavy vehicle drag by 25%

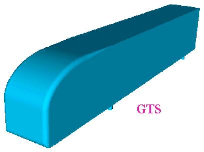
Approach:

- **Identify major contributors to drag**
  - Experimental discovery and testing
  - Modeling and simulations
- **Design drag reducing add-on devices**
  - Utilize accumulated knowledge gained in both experiments and simulations
- **Evaluate and test add-on devices using**
  - Experiments
  - Modeling and simulation
  - Track test
  - Road test
- **Get drag reducing add-on devices on the road**
  - Assist with operational and design concerns

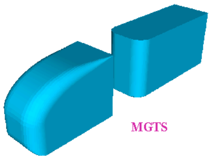
3

Heavy vehicle models are used with increasing realism to understand the flow physics

- Ground Transportation System (GTS)
  - Simplified tractor-trailer geometry
  - Extremely useful in validation of computational models
- Modified GTS
  - Testing drag reduction concepts at low Reynolds numbers
- Generic Conventional Model (GCM)
  - More representative of a modern tractor-trailer geometry
  - Missing: wheel wells, realistic tires, realistic underbody, flow through engine
- Modified GCM
  - Improved geometry fidelity over GCM
  - Include: wheel wells, realistic tires, improved underbody
  - Missing: flow through engine

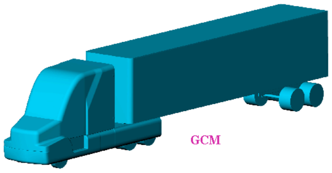


GTS



MGTS

MGCM, SOLUS



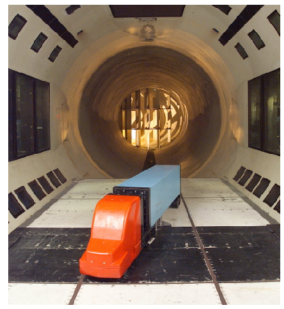
GCM

4

Extensive experimental testing was performed on increasingly higher fidelity heavy vehicle models

NASA Ames Research Center

- 3'x4' wind tunnel, GTS, MGTS
  - 300,000 Reynolds number
  - Testing trailer base and underbody drag reducing concepts
- 7'x10' wind tunnel, GTS, MGTS, GCM
  - 2 million Reynolds number
  - Testing drag reducing concepts and flow physics
- 12' pressure wind tunnel, GCM
  - Full-scale Reynolds number is achieved!
  - Several drag reducing aero-devices were tested



NASA Ames 12' pressure wind tunnel

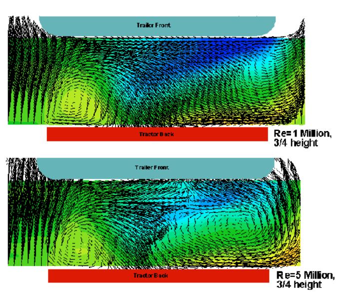
University of Southern California (USC)

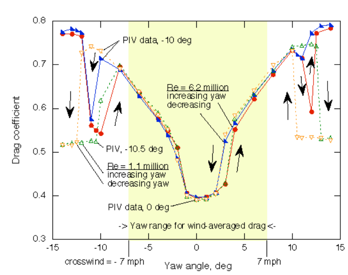
- 3'x4' wind tunnel, MGTS
  - 300,000 Reynolds number
  - Testing gap and trailer base drag reducing devices and flow physics

5

Significant knowledge was gained through experimental testing

- Improved understanding of flow physics
- Generated comprehensive data set for computational validation
  - Wind averaged aerodynamic forces
  - Surface pressure, steady and time dependent
  - Flow visualization, Particle Image Velocimetry
- Demonstrated Reynolds number effects
  - Reynolds number effects were relatively small above ~1.5 million.
  - Care should be taken in interpreting smaller-scale data





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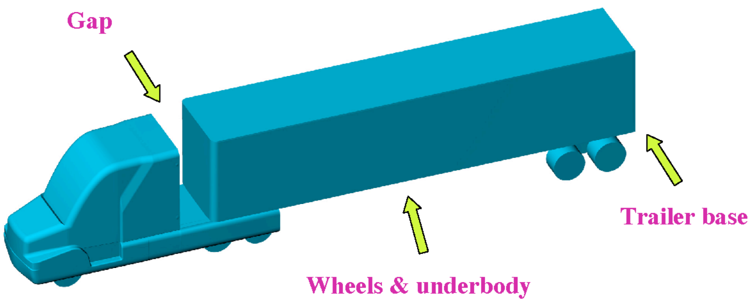
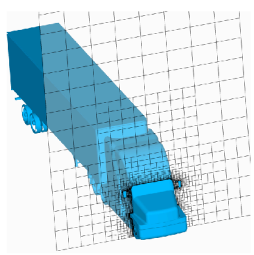
Critical drag producing regions were identified



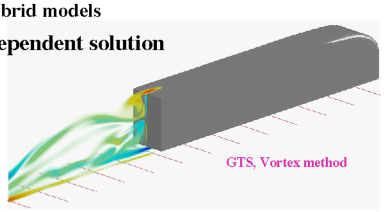
7

A variety of computational approaches were investigated

- Navier-Stokes formulation, steady and time-dependent solutions
  - Discretization schemes, FD, FV, and FEM method
  - Turbulence modeling, RANS, LES, and hybrid RANS/LES
  - Structured, unstructured, and overset meshes
  - Boundary representation
    - Boundary fitted
    - Cartesian mesh with trim cells to fit boundaries
    - Cartesian mesh with immersed boundary technique
- Vorticity equation formulation, time-dependent solution
  - Meshless, requires only a surface mesh
  - Turbulence modeling, LES, DNS, and hybrid models
- Lattice Boltzmann formulation, time-dependent solution



Immersed boundary method



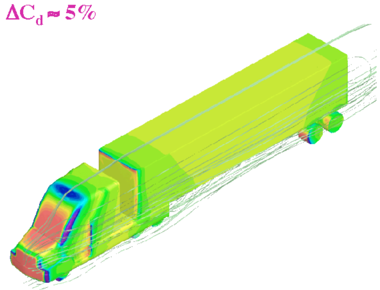
GTS, Vortex method

8

Guidelines were established for accuracy of computational predictions

Prediction of aerodynamic forces and the flow field are significantly influenced by

- **Geometry characteristics,** $\Delta C_d \approx 15\%$
- **Turbulence modeling selection,** $\Delta C_d \approx 5\%$
- **Grid resolution,** $\Delta C_d \approx 10\%$
- **Large yaw angles,** $\Delta C_d \approx 25\%$



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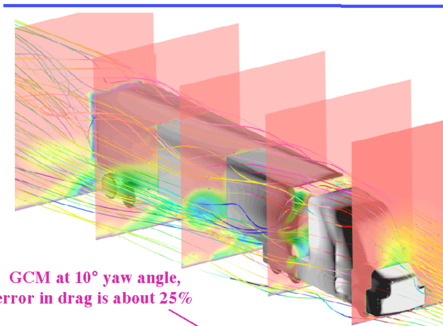
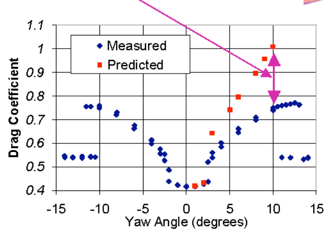
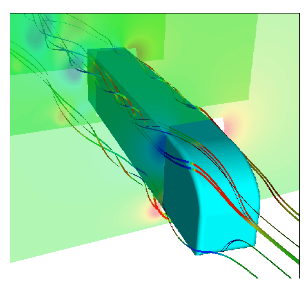
Computational prediction at large yaw angles requires extra care



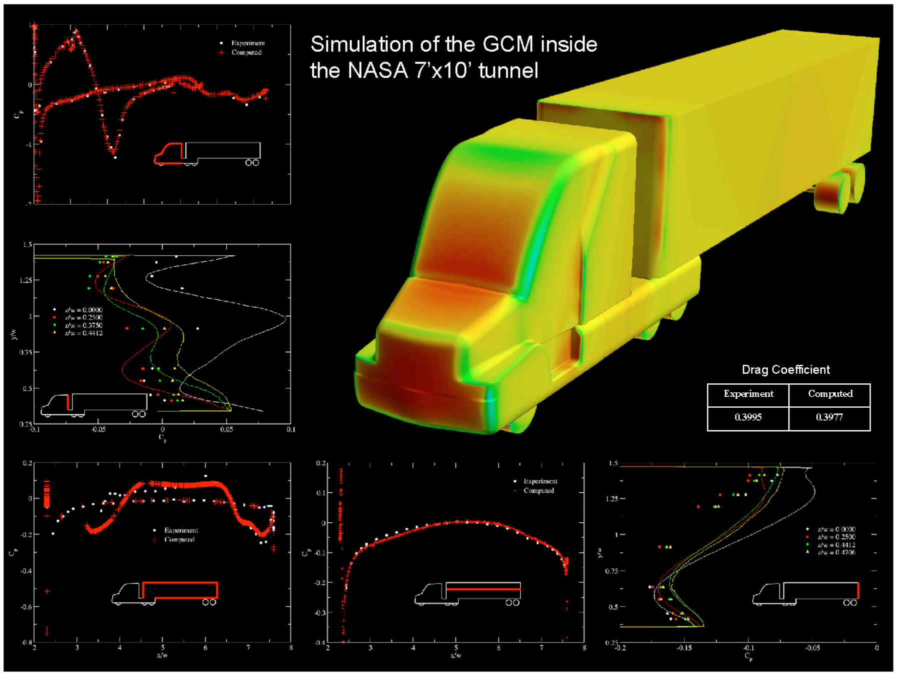
GCM at 10° yaw angle, error in drag is about 25%





GTS at 10° yaw angle, error in drag is about 5%

10

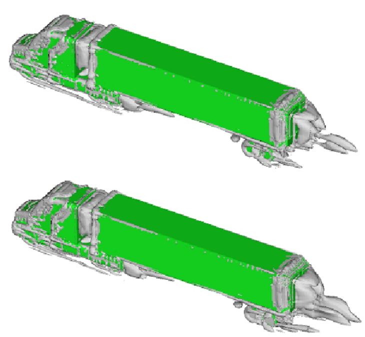


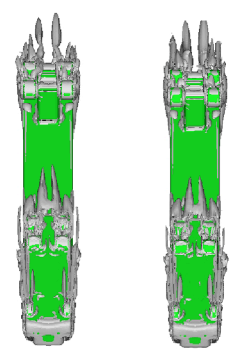
Influence of wheel rotation on drag (ΔC_d = 4.5%)

URANS simulation of GCM with rotating wheels at 0° yaw

URANS – No rotation

URANS – Rotation





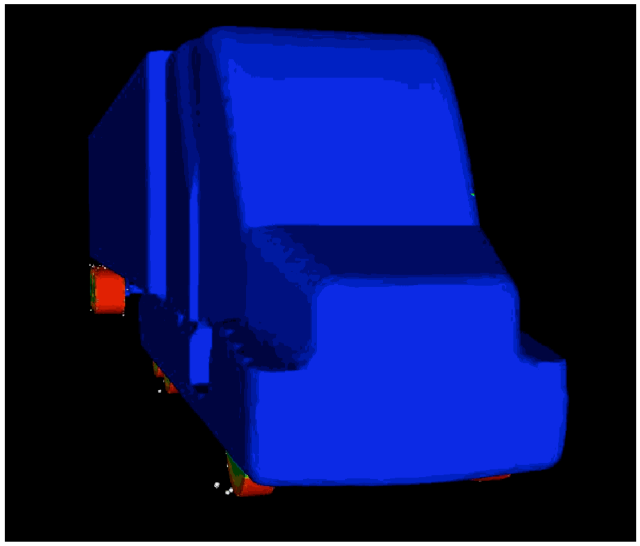
URANS – No rotation

URANS – Rotation

Configuration	C_d at 0° yaw
Baseflaps w/ no wheel rotation	0.422
Baseflaps w/ wheel rotation	0.441 (+4.5%)

12

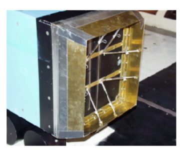
URANS simulation of GCM with rotating wheels



13

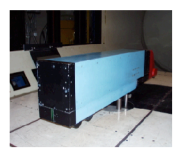
A variety of drag reducing add-on devices are tested

- **Trailer base**
  - **Base flaps**
  - **Boat-tail plates**
  - **Base blowing**
  - **Ogive boat-tail**
- **Underbody**
  - **Belly box**
  - **Side skirt**
  - **Wedge**
- **Gap**
  - **Splitter plate**

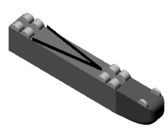


Base flaps

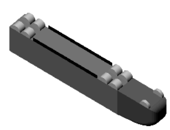
Boat-tail plates



Belly box

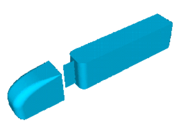


Wedge

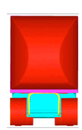


Side skirt

Base blowing



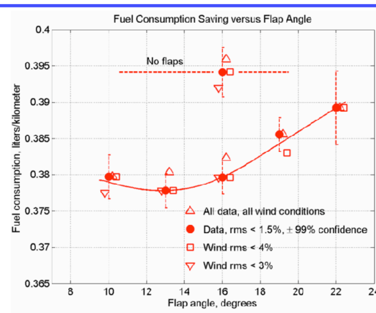
Splitter plate

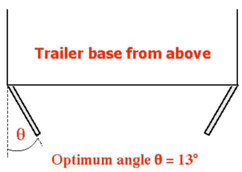


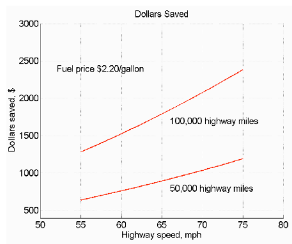
Ogive boat-tail

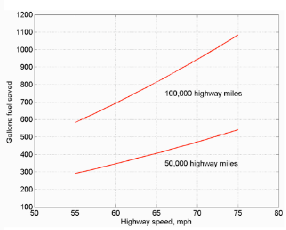
14

Base flaps tested at Crows landing (ΔC_d = -8.6%)





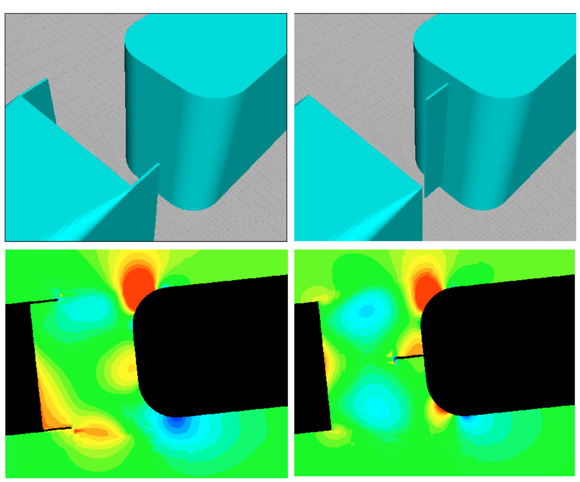




15

Gap add-on devices reduce drag by ~5%

The trailer splitter plate reduces drag without a significant increase in side force.



MGTS model,

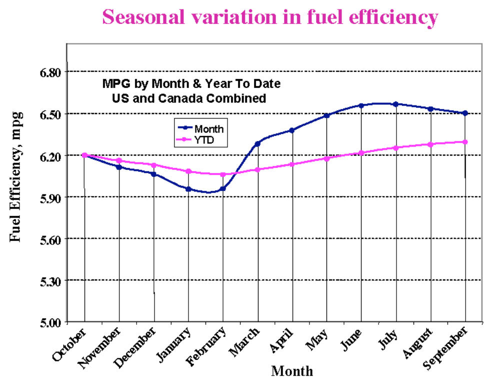
6° yaw,

non-dimensional gap of 0.65,

Re = 340,000

16

Effect of climate variation on aerodynamic drag



$$Drag = 1/2\ \rho\ V^2\ C_D$$

ρ = air density
V = wind speed over truck
C_D = drag coefficient

About 50% of the observed fuel efficiency variations can be attributed to wind and temperature variation during the year

- Change in air density has the largest effect

17

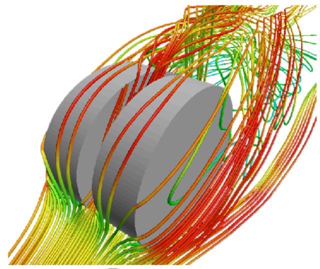
New initiatives related to safety

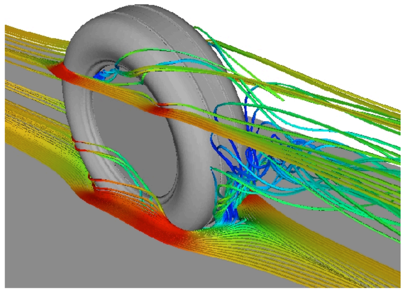
- **Splash and spray**
  - Tire aerodynamics
  - Experimental investigation at USC
- **Empty coal car aerodynamics**
  - Drag reduction concepts
- **Wind-induced overturning**

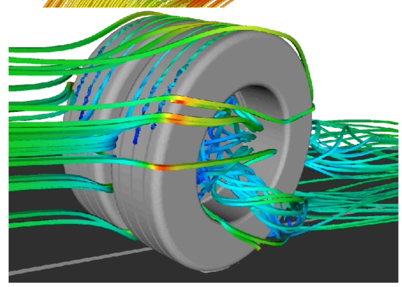
18

Flow field around tires is essential for spray formation and propagation

- Tire and wheel geometry significantly influences flow structures
- Spray transport is coupled to aerodynamics







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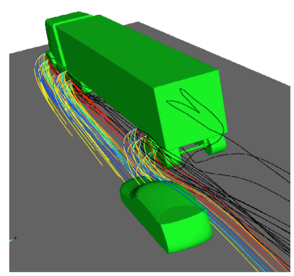
Develop modeling capabilities for splash and spray

- Goal
  - Understand important physics using state-of-the-art multiphase modeling tools coupled to realistic flow solutions
  - Explore various mitigation concepts
  - Design and test devices
- Challenges
  - Unsteady flow
  - Complex geometry
  - Splash and spray formation/interaction
- Advantages
  - Expertise
  - Resources
    - Simulation tools
    - Computer hardware



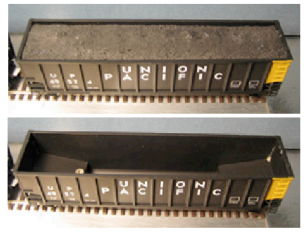
Particle trajectories around a truck and impact on passing car

20

Investigate empty coal car aerodynamics

- 2002 U.S. Statistics on coal usage*
  - 1 billion tons used, 66% carried by rail
  - 44% tonnage, 25% loads, 21% revenue
  - 85% by unit trains (50+ cars)
  - Average coal haul = 696 miles
- Aero Drag Reduction Potential
  - Fuel consumption: empty ≈ full
  - Aero drag ~ 15% of round-trip fuel consumption
  - 25% reduction → 5% fuel savings (75 million gal)

* The Rail Transportation of Coal, AAR, Vol. 5, 2003



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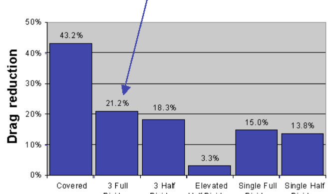
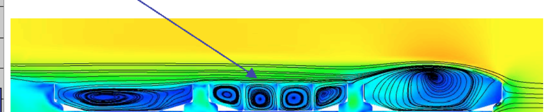
Designed drag reducing devices for an empty coal car

Add-on device

NASA Ames wind tunnel





Simulation, particle traces

22

Summary

- Extensive experimental testing was performed on increasingly higher fidelity heavy vehicle models
- Improved understanding of flow physics was obtained through knowledge gained with experimental testing
- Applicability of a variety of computational approaches to bluff body aerodynamics were investigated
- Established guidelines for accuracy of computational prediction
- Immersed boundary method can offer significant speedup in meshing complex geometries
- URANS simulations were performed on GCM with base flaps including the influence of rotating wheels
- Base flap and gap splitter plate were tested using modeling and simulations
- Starting to develop modeling and simulation capabilities for splash and spray that include tire aerodynamics
- Designed and tested drag reducing add-on devices for empty coal cars

Achievements: Summary

GOAL: 25% Drag reduction

Perhaps changes in Cd are adequate (?)

- Experimental tests with increasingly detailed models have illustrated Re effects and important flow physics
  - Need to consider even higher fidelity models (for example underhood effects)
- Full scale testing of devices has shown effectiveness of base flaps
- Simulations have been done with variety of computational approaches

Achievements: Summary (Simulations)

Guidelines for simulations have been established

- Need to exercise care in geometry, meshing, & turbulence model especially for high yaw angles
- Mesh generation is challenging – consider other methods that eliminate this issue such as IB, vortex or lattice Boltzmann (Powerflow).
- Integrated quantities can be misleading, need to be careful!
  - Ex: base pressure is wrong then drag reduction due to base modification is likely wrong
- Should consider unsteady and wheel rotation effects in CFD
- Considering other areas such as safety (splash & spray) and coal cars.
  - Safety: modeled wheel aero and exploring spray
  - Coal: Illustrated PRACTICAL DR concepts

Achievements: Summary

- Discussion highlighted many issues for path forward:
  - NRC Canada has explored many of these concepts & full-scale testing; should collaborate
  - Need to involve industry sooner in process to consider practical constraints, but at same time should be forward-looking about tech changes
  - Underhood/thermal control needs to be considered (emissions regs) but hard since temp data not avail.

Heavy Vehicle Drag Reduction Issues

- Getting improvements on the road
- Aerodynamic prediction capability
- Money…

Supporting the NASA Mission

Getting Improvements on the Road

- Testing requirements/standards
  - SAE Type 1 road tests mandatory?
  - Can fuel-flow meter readings or other test procedures be developed that would be acceptable?
  - Can CFD and/or wind tunnel results suffice?
- Operator/driver reluctance
  - Time required to operate devices
  - Reliability and damage tolerance
- Regulatory vs. economic incentives
  - Will the current high fuel prices start a trend?

Aerodynamic Prediction Capability

- Flow physics modeled accurately?
  - Wake
  - Gap
  - Underbody, wheels/tires, & road
  - Cooling air
- Turbulence models and alternative computational methods
- What experiments are needed?
- Absolute drag accuracy
  - What is current state of the art?
  - How much better than in 1998?
- Drag delta capability
  - Geometry changes affecting drag
  - Magnitude of drag change that can be discerned
  - Current capability/understanding?

Ames Research Center

Money

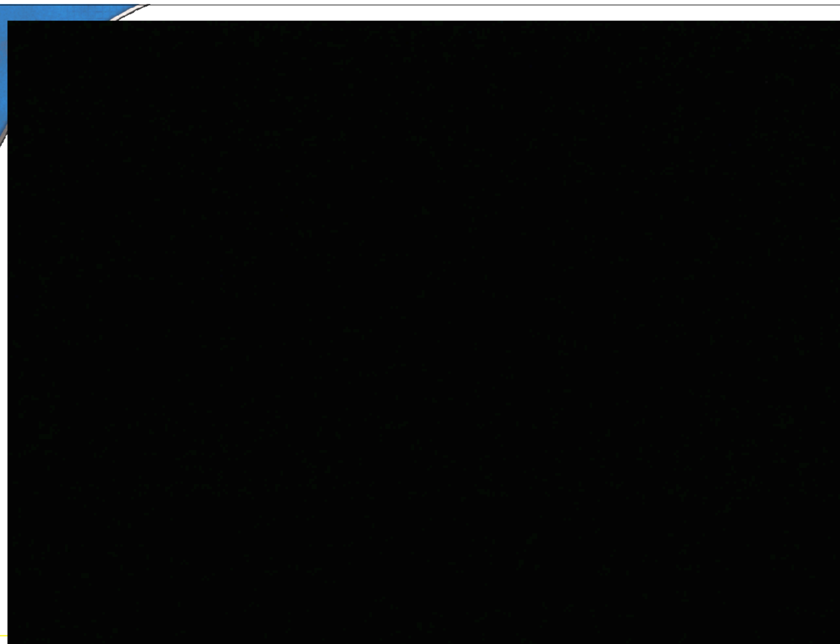
- Never enough for researchers
  - What are the areas that need to be addressed?
  - Other than DOE, what are the appropriate funding agencies/mechanisms?
- What payback do operators need to justify investing in aero improvements?
  - What productivity hits are allowable?
  - How much effort goes into aero improvements at OEMs? Does it "pay"?
- Are current and projected fuel costs high enough to raise priority of aerodynamic drag?

Overview of Michelin Research on Splash, Spray, and Aerodynamics

Ralph Hulseman
Michelin Americas Research and Development Corporation
12 May 2005

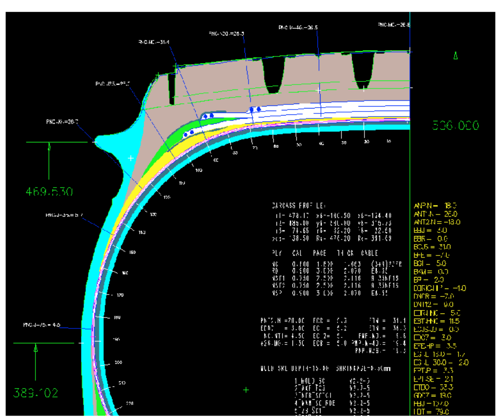
Anti-splash Feature on the Tire

“Chine”



Anti-Splash

- Objective:
  - Redirect water ejected from tire contact patch
  - Maintain all other types of tire performance

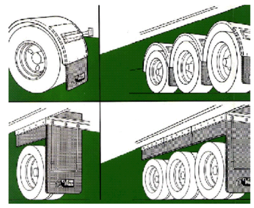


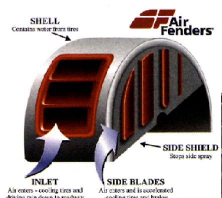
Technical Results Summary

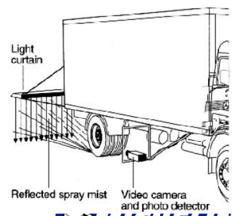
- One tire size studied:
  - Up to 4x reduction in splash height
  - Large improvement of visibility for vehicle passing the truck creating a splash.
- Largest improvement observed when fitted to all axles, but, relative importance by axle position and vehicle type is not well understood.
- +5% manufacturing cost increase per tire.
- No major technical barriers encountered but experience is limited to one tire size (recapping, endurance, interference of duals, manufacturing)
- First size developed by trial and error. Design algorithms and simulation tools are needed to optimize for various tire sizes and vehicle configurations.
- Interactions with vehicle aerodynamics and spray formation are unknown.

Heavy Truck Spray

Anti Spray Devices & Test



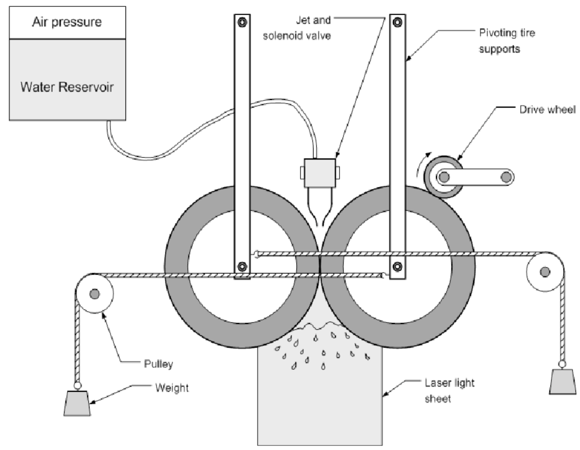




Mythology of Tires and Spray

- Some comments from the trucking industry:
  - “All the spray comes from the grooves in a rib tire”
  - “A block tire is worse than a rib tire”
  - “Super singles are better than duals”
  - “Nothing can be done with tires to reduce spray”
- However:
  - No studies of the physics of creation of spray by the tire are known.
    - Michelin / USC study underway
  - Tires have a measurable effect on vehicle aerodynamics
    - Michelin / Georgia Tech study.

work with USC



MICHELIN
A better way forward

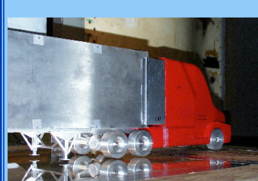
MICHELIN

Quantification of Tire Aerodynamics on Overall Heavy Truck Aerodynamics

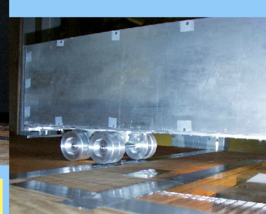
by

Robert J. Englar, Georgia Tech Research Institute
Ibrahim M. Janajreh, PhD, Michelin Americas R&D Corp.

Georgia Tech Research Institute



How do the Aerodynamics of Flows around Tires......

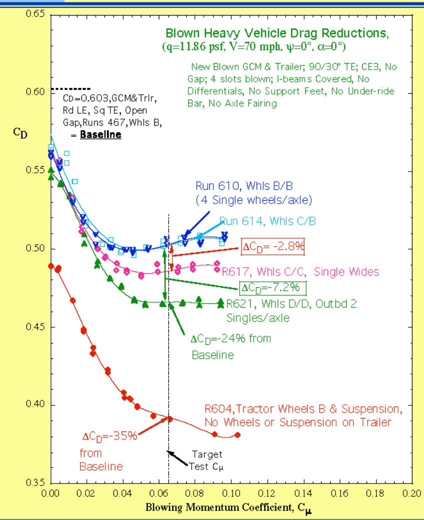


...and Under-body Flows affect the...

...Total Aerodynamics of Advanced Heavy Vehicles?

SAE 2004-01-2695

Wind Tunnel Results: Effect of Wheel Type on Blown Pneumatic Heavy Vehicle Drag



- Tire Blockage ahead of the Blown Trailing Edge Increases C_D
- Reduced Tire Thickness Reduces Blockage & Drag since Tire Wake is less
- Originally Postulated 1% Drag Reduction due to Wheels/Tires Appears Very Feasible
- Best Configuration (lowest C_D) is Trailer Wheels OFF (but not too practical) = No Wake

[Cμ is Blowing Jet Momentum Coefficient; Cμ= Non-dimensional Jet Velocity x Mass Flow]

Questions?

Issues Summary

➢Devices aren't on the road
- Long history of studying devices
- Need engineering/marketing for immediate impact

➢Data isn't readily available
- Intellectual property.....CRADA?
- Literature survey
- What is acceptable? necessary?
  - Absolute vs. % drag reduction
  - Wind tunnel conditions
  - Under hood considerations
  - 1/10th model w/ 40 devices: balance measurements

1

Issues Summary

➢Industry disconnect
- Where are the trailer people?
- What are the operational restrictions that limit device use?
  - Brake light visibility w/ base flaps?
  - Restricted access to trailer
- What has been tried? Was it worth it?
- Why aren't systems integrated?
- When will fuel prices force the issue?
- Industry education

2

Issues Summary

➢Funding

- Priorities.....
- CRADA, DOE money generally goes to the labs, IP can be protected
- DOT may have interest in splash and spray
- OEM’s and tire manufacturers don’t get credit for reducing fuel consumption from EPA
- EPA – Smartway? Program to give credit

3

Path Forward

Heavy Vehicle Aerodynamic Drag
DOE Consortium Working Group Meeting

Rose McCallen

Lawrence Livermore National Laboratory

May 12, 2005

FY06 plans address issues and push into new areas

Get technology on the road

- Working with manufacturers/fleet – DOE Industry Consortium
- Full-scale testing – NRC Canada

System integration

- Reduction in fuel use
- Enhanced safety

engine cooling

Computational modeling that adequately captures reality

- Model scale and fidelity
- Multi-physics
- Operational environment

brake cooling

New areas

- Splash & spray, brake cooling, underhood
- Railcars

Funding

- Government teaming & leveraging funds

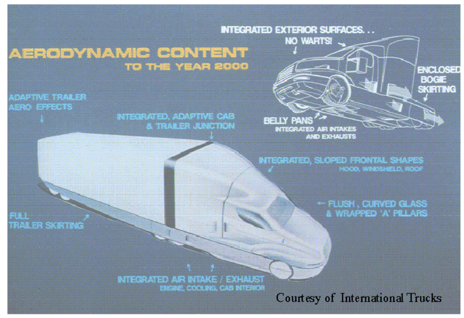
System integration for enhanced safety and performance WHILE reducing aero drag

Reduction in fuel use

- Underhood
- Underbody
- Wheel aero (duals vs. singles)
- Mirrors, fenders, etc.

Enhanced safety

- Vehicle stability – wind loads
- Stopping distance – brake cooling
- Splash & spray



Courtesy of International Trucks

Windload Stability: Overturning is countered by weight, dependent on roadway, and sensitive to wind gusts

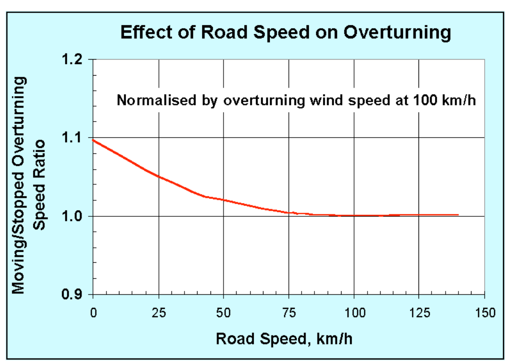
Quasi-static analysis provides order-of-magnitude results

Overturning wind speed, m/s

$$V_o = \sqrt{\left(\frac{2}{\rho}\right)\left(\frac{yW}{C_R A_S h}\right)}$$

- y is track half-width
- C_R is aero rolling moment coefficient at 90° yaw
  - Conservative assumption is C_R = 1.0 at 90°
- W is weight in Newtons
- A_S is side area
- h is total height

Overturning wind decreases with forward speed



NRC·CNRC

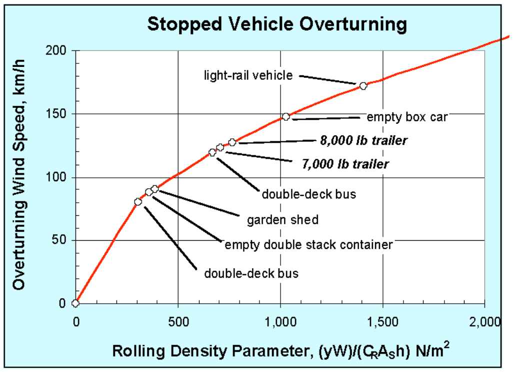
Overturning speed depends on rolling density

Turnover speed

8,000 lb trailer - 127 km/h (79 mph)

7,000 lb trailer - 119 km/h (74 mph)

The lower speed has a higher probability of occurrence



NRC·CNRC

Vehicle aerodynamics impact brake performance

Aerodynamics

Brakes operating at performance limits – cooling issues

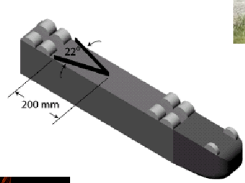
Aero drag reducing devices can make problem worse

- Need more braking power
- Can redirect brake cooling flow

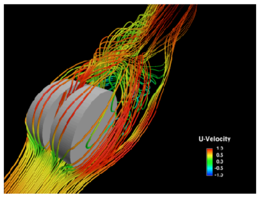
Challenges

Aerodynamics

- Rotating wheels and tires
- Wheel wells
- Underbody



Underbody wedge

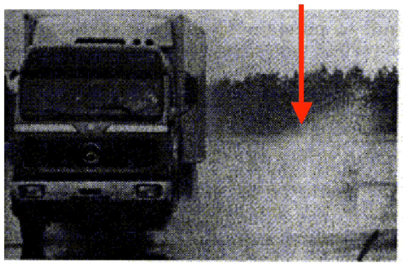


Aerodynamics of dual tires

Vehicle aerodynamics impact splash & spray

Car disappears behind spray

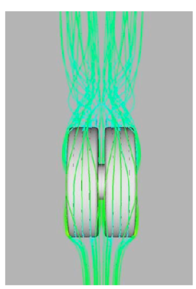
Fender fairings mitigate spray but do not prevent splash

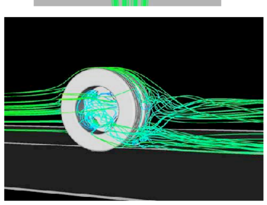


1993 Annual Review of Fluid Mechanics
Photos Courtesy of Mercedes-Benz

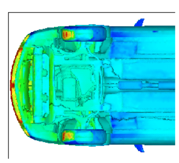
System integration requires high fidelity, multi-physics computational modeling

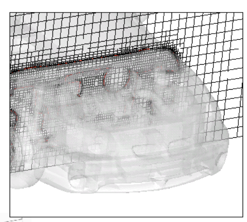
Tire/wheel details

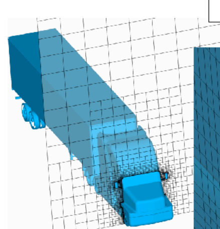


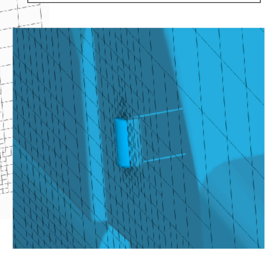


Immersed boundary method
Courtesy of DOE-ASC, Stanford University

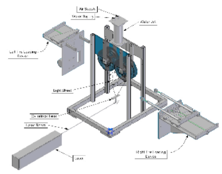








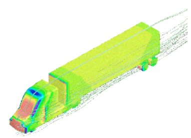
Integrated DOE/DOT effort = benefits for industry & nation



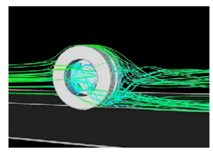
***Experiments** – DOE funding*
- Fundamental physical insight
- Realistic geometries & devices
- Simulation validation

Real-world application
- *Intelligent* device design
- Field testing

IMPROVE SAFETY



***Computations** – DOE funding*
- Investigate key physics
- System optimization
- Leverage national lab resources to advance the state-of-the-art



FY06 plans address issues and push into new areas

Get technology on the road

Working with manufacturers/fleet – DOE Industry Consortium

Full-scale testing – NRC Canada

System integration

Reduction in fuel use

Enhanced safety

engine cooling

Computational modeling that adequately captures reality

Model scale and fidelity

Multi-physics

Operational environment

brake cooling

New areas

Splash & spray, brake cooling, underhood

Railcars

Funding

Government teaming & leveraging funds

Discuss two separate and unrelated experimental programs

Briefly describe work on underhood flow management (proposed and awaiting funding)

Spend more time on preliminary results for the production of droplet sprays from tires

Aircraft Inspired Approaches to Management Of Cooling-Flow

James Bell
James Ross

NASA Ames Research Center

Separate flows for separate tasks

Experimental Program

Step 1

Use interior ducting to partition cooling air through radiator from cooling air for specific accessories

Provide for control of exit air flow for both of these functions

Step 2

Provide separate air passages for radiator cooling air and for accessories air

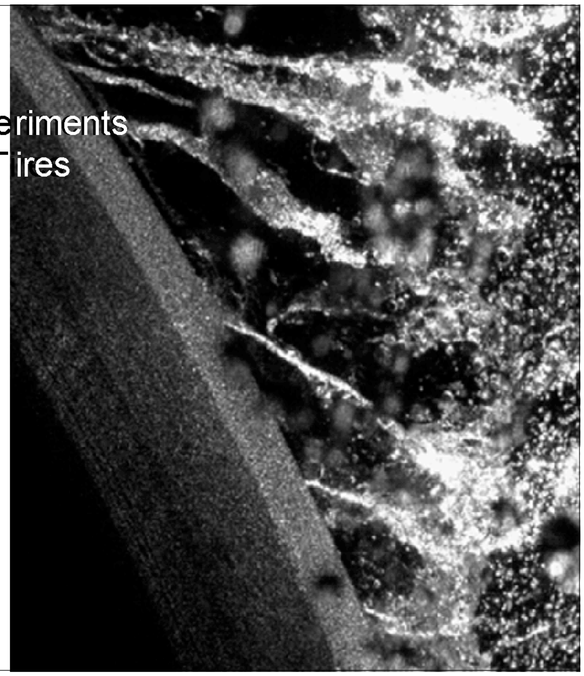
Diagnostics

Measure pressures throughout the engine compartment

Use temperature-sensitive paint for temperature measurement

Use DPIV-for velocity field information

Preliminary Experiments on Spray from Tires



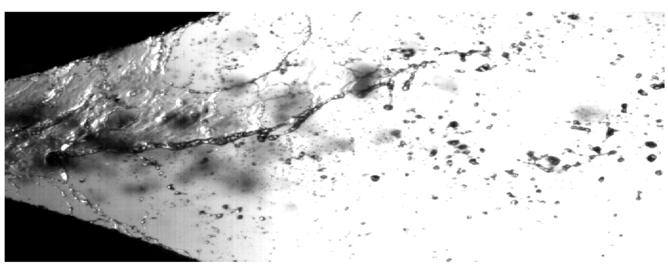
Fred Browand
Adam Fincham
Dennis Plocher
Tai Merzel
Charles Radovich

University of Southern California

Experiments on Spray from Tires

Water droplets often form as a result of the break-up of jets—or sheets—of fluid.

This is true in the case of tire-initiated spray also.



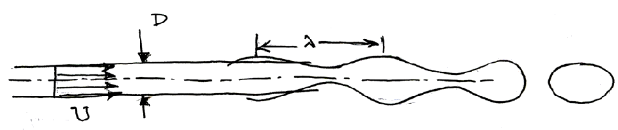
We must understand the physics of jet and sheet break-up.

Experiments on Spray from Tires

Rayleigh's problem: The solitary jet

Oscillations in the jet column form from random disturbances, and grow because the jet is unstable.

After sufficient disturbance growth, droplets are formed.



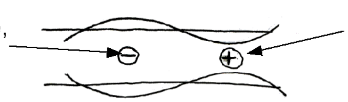
Unstable waves occupy: Wave speed = U, $\pi < \lambda/D < \infty$

Most unstable wave yields droplets of size: $d_{droplet} = 1.89\ D$

Experiments on Spray from Tires

The instability is driven by surface tension.

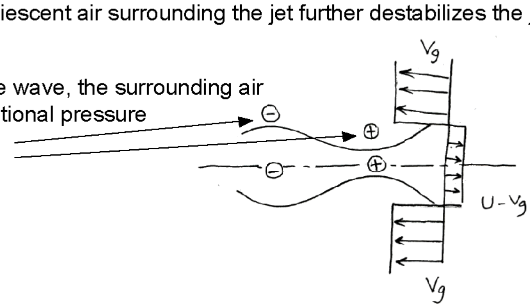
Radius larger here, pressure is less



Radius smaller here, pressure is greater

Addition of quiescent air surrounding the jet further destabilizes the jet.

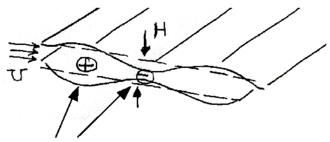
Riding with the wave, the surrounding air produces additional pressure differences.



Experiments on Spray from Tires

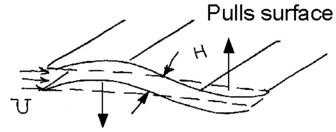
Sheets

Deformed sheets are stable when by themselves.



Surface tension creates pressure difference that drives fluid from crest to trough.

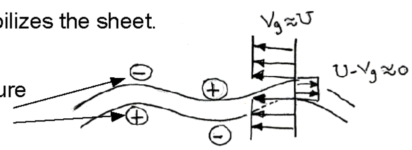
Surface tension
Pulls surface up



Surface tension pulls surface down

… but a surrounding air mass destabilizes the sheet.

Sheet is driven laterally by the pressure differences in the surrounding air.



Experiments on Spray from Tires

Sheets

Sinuous disturbances are usually more unstable than varicose disturbances. When the amplitude of the wave is sufficiently large the sheet breaks up into droplets comparable in size to the local sheet thickness.

Since the sheet is driven unstable by the inertia of the surrounding air, the larger the inertia the more violent the wave growth will be.

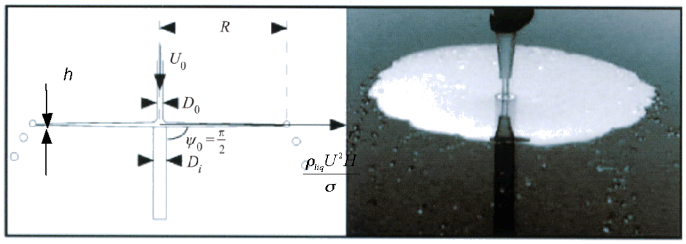
The effective inertia is measured—relative to (restorative) surface tension—by the Weber number.

$$We = \frac{\rho_{liq} U^2 H}{\sigma} \quad \left(or \quad \frac{\rho_{liq} U^2 D}{\sigma} \; for \; the \; jet\right), \; \sigma \; is \; surface \; tension$$

The larger the Weber number, the more violent the sheet (or jet) break-up will be, and the smaller the droplets will be.

Experiments on Spray from Tires

Examples: Clanet & Villermaux (JFM 2002)



Sheet thins as R grows: $\frac{R}{D_0} \approx \frac{We}{16}$, $\frac{h}{D_0} \approx \frac{10^{-1}}{We}$

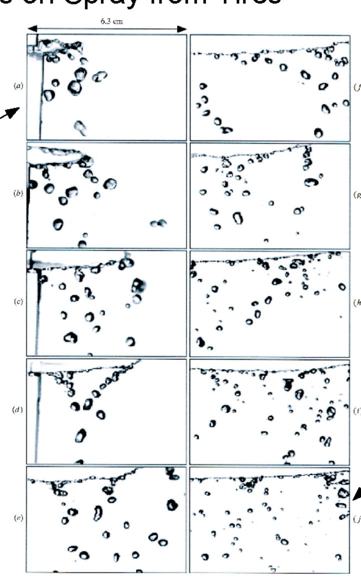
For *We = 1000*, $h/D_0 \approx 10^{-2}$

For D_0 = *1 cm*, *droplet size* $\approx h \approx$ *100* μm

Experiments on Spray from Tires

Examples:
Clanet & Villermaux (JFM 2002)

We $\approx$ *150*



We $\approx$ *1000*

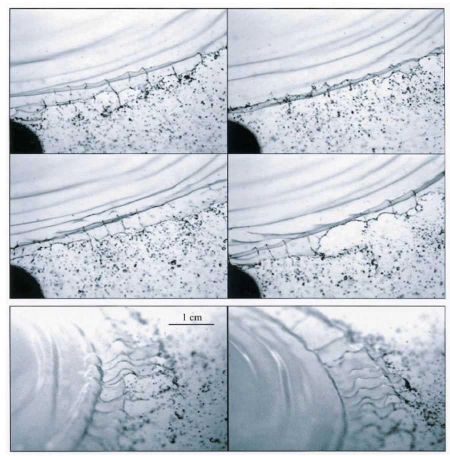
Experiments on Spray from Tires

Examples:
Villermaux & Clanet (JFM 2002) Above We ≈ 1000, the K-H instability becomes dominant.

$$\frac{d_{droplet}}{D_0} \approx \frac{1}{(\frac{\rho_{air}}{\rho_{liq}})^{2/3}} \frac{1}{We} \approx \frac{90}{We}$$

For *We* ≈ *40,000*, $d_{droplet}/D_0 \approx 0.0025$

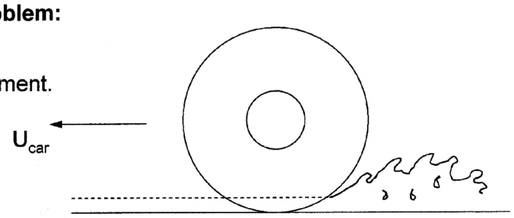
For $D_0 = 1$ *cm*, $d_{droplet} \approx 25\ \mu m$



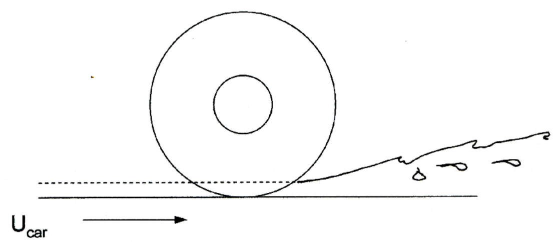
Experiments on Spray from Tires

Return to the tire problem:

Tire rolling on wet pavement.

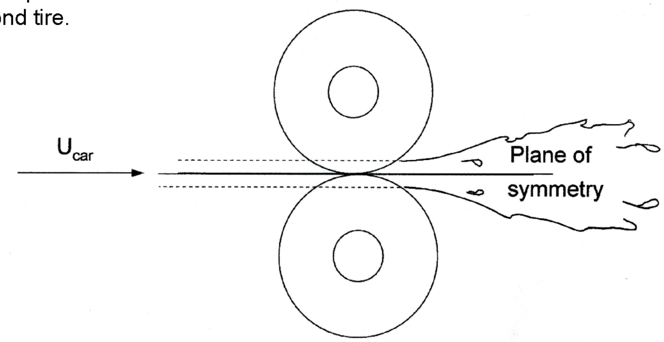


Riding with the car.

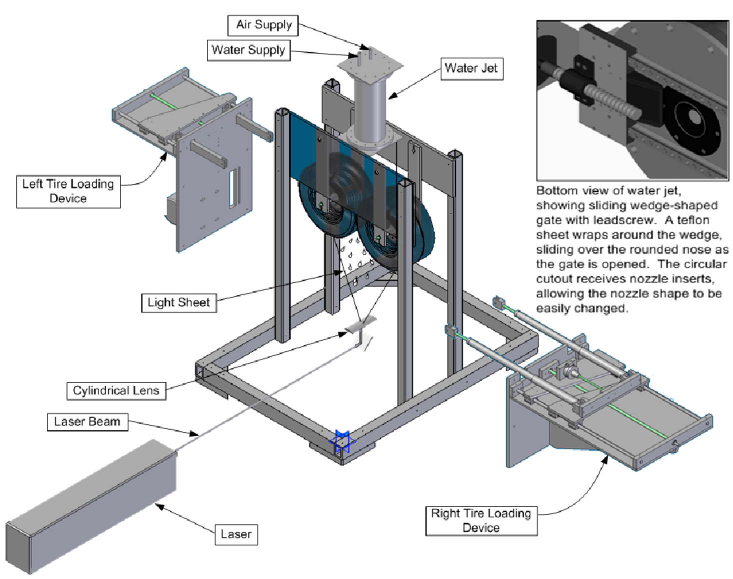


Experiments on Spray from Tires

Now replace the road with a second tire.



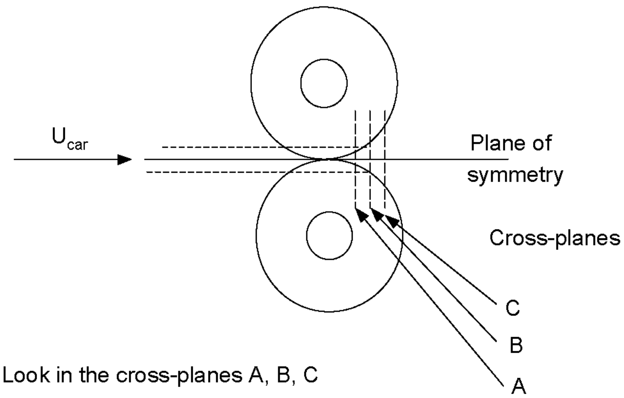
Experiments on Spray from Tires



Bottom view of water jet, showing sliding wedge-shaped gate with leadscrew. A teflon sheet wraps around the wedge, sliding over the rounded nose as the gate is opened. The circular cutout receives nozzle inserts, allowing the nozzle shape to be easily changed.

Experiments on Spray from Tires

How do “jets” and “sheets” fit the tire spray picture?

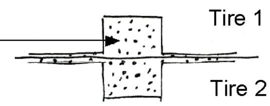


Look in the cross-planes A, B, C

Experiments on Spray from Tires

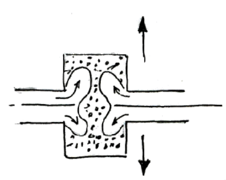
How do “jets” and “sheets” fit the tire spray picture?

Water filling single, circumferential groove



Section A

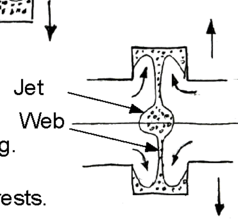
Tires move apart. Water is ejected from tread groove.



Section B

Central jet is unaffected by acceleration. It breaks up due to Rayleigh instability.

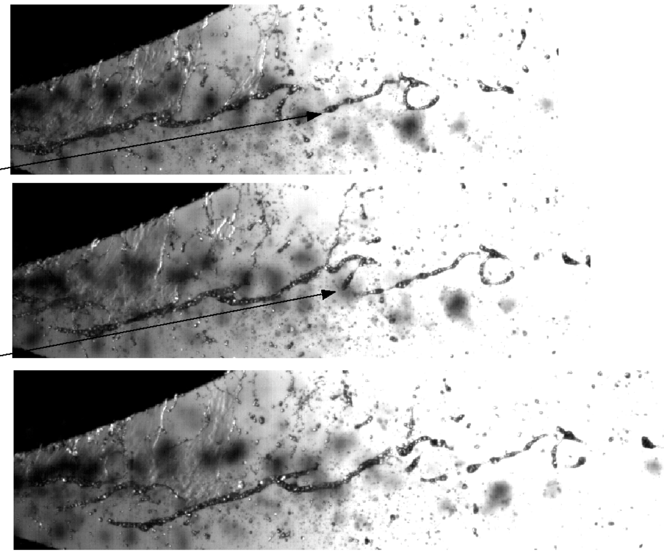
Web continually thins as a result of stretching. Waves on web travel in the downstream direction. Web appears to break between crests.



Section C

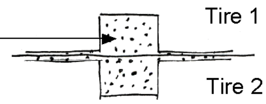
Experiments on Spray from Tires

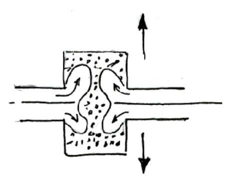
Central jet instability



Experiments on Spray from Tires

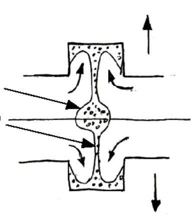
How do “jets” and “sheets” fit the tire spray picture?





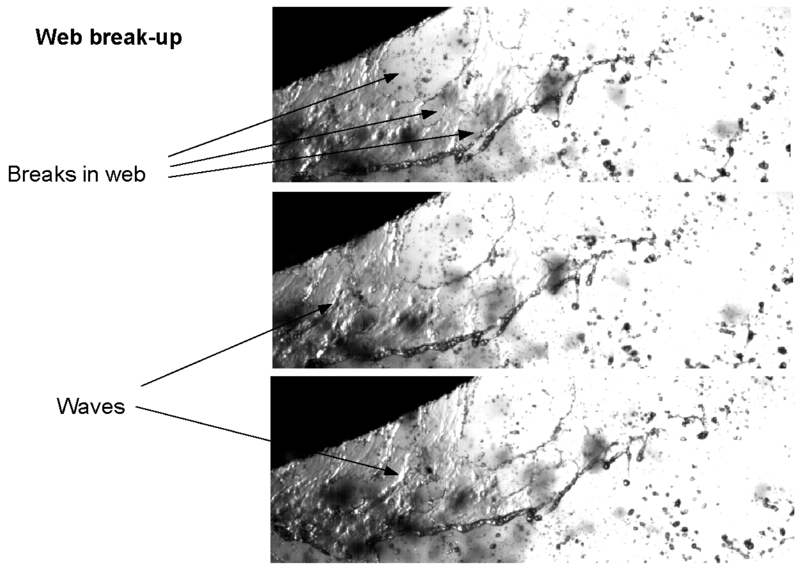
Central jet is unaffected by acceleration. It breaks up due to Rayleigh instability.

Web continually thins as a result of stretching. Waves on web travel in the downstream direction. Web appears to break between crests.



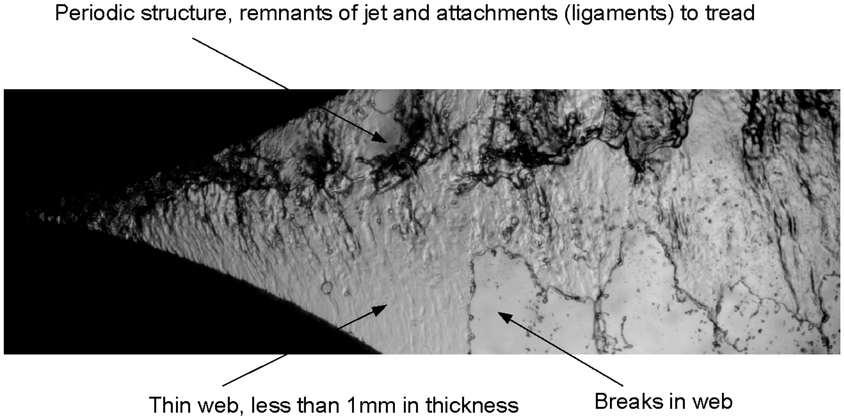
Experiments on Spray from Tires

Web break-up



Experiments on Spray from Tires

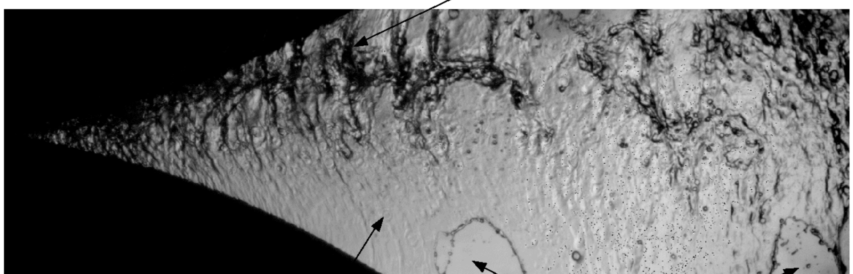
Another example, water delivery speed and tire speed approximately matched



Experiments on Spray from Tires

Another example, water delivery speed and tire speed approximately matched

Periodic structure, remnants of jet and attachments (ligaments) to tread



Thin web, less than 1mm in thickness

Breaks in web

Experiments on Spray from Tires

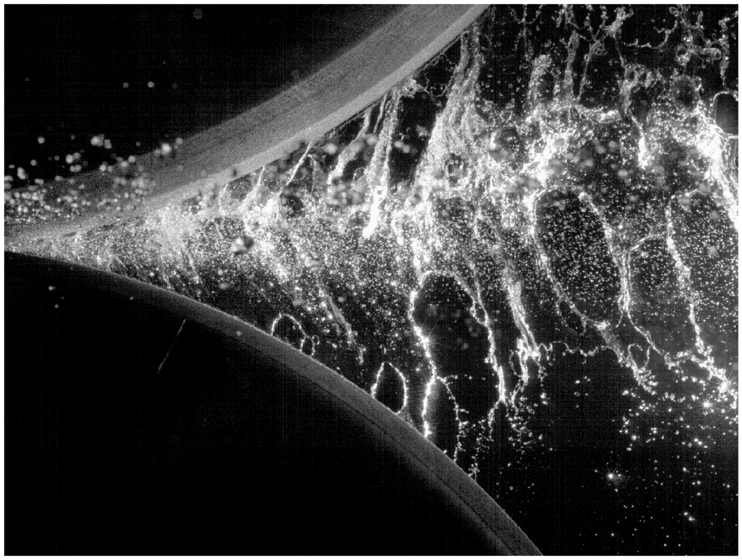
High-speed digital photography

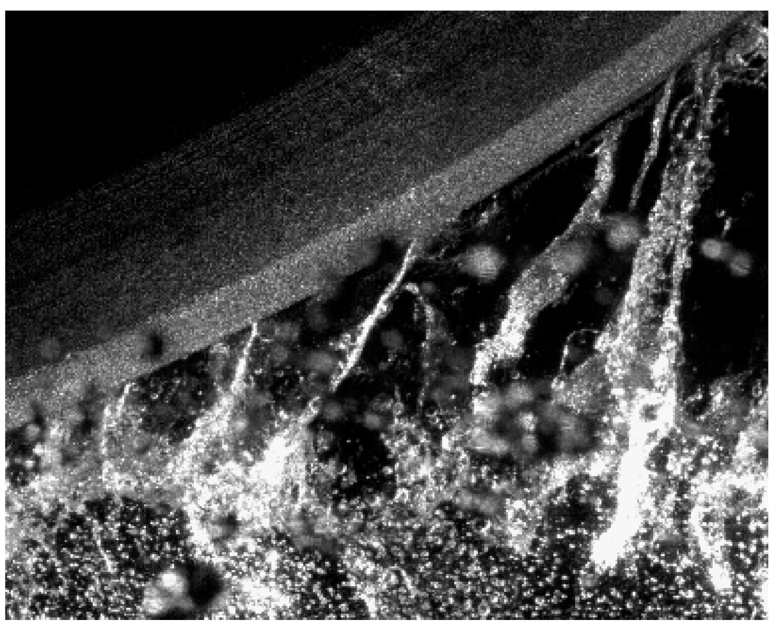
IDT digital camera from Integrated Design Tools, Inc.
1260x1024 pixels
Data storage, 1 gigabyte, expandable
Framing rate and exposure time separately variable
- currently operating with back-lighting at 2-4 μs exposure and framing of 1600-1700 fps with 250 mm x 70 mm field of view
- suitable for time history, and for Digital Particle Image Velocimetry (DPIV)

Laser sheet photography

2-tube Yag laser 150 mJoules per pulse
10 nanosecond pulse time
Sheet width variable—in this case $\approx$ 2-3 mm
Laser repetition rate $\approx$ 10 Hz
Operating modes
- single-tube, 10 Hz
- dual tube, 10 Hz, but variable time between pulses
- suitable for DPIV

Experiments on Spray from Tires





Experiments on Spray from Tires

Important non-dimensional parameters

$$Weber\ number\ = \frac{\rho U^2 H}{\sigma}$$

$$\frac{Jet\ speed}{Tire\ speed} = \frac{U_{jet}}{U_{tire}}$$

$$\frac{Jet\ volume\ flow}{Tire\ "swallowing"\ flow} = \frac{U_{jet} A_{jet}}{U_{tire} A_{tread}}$$

$$Reynolds\ number = \frac{UH}{\upsilon} >> 1\ \ and\ unimportant$$

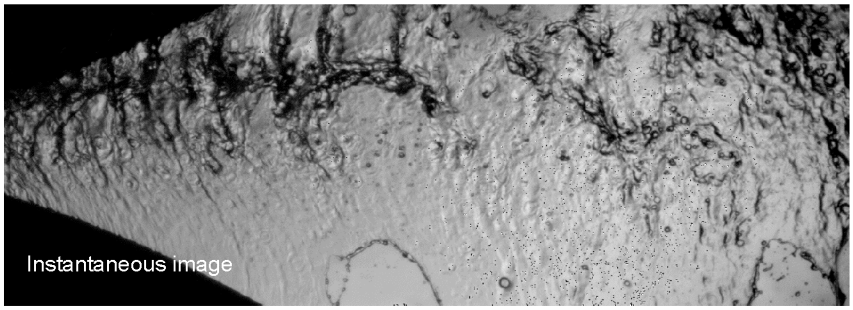
Experiments on Spray from Tires

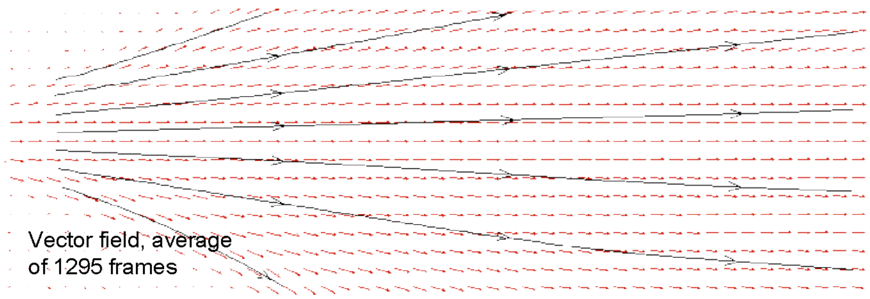
Where we are today

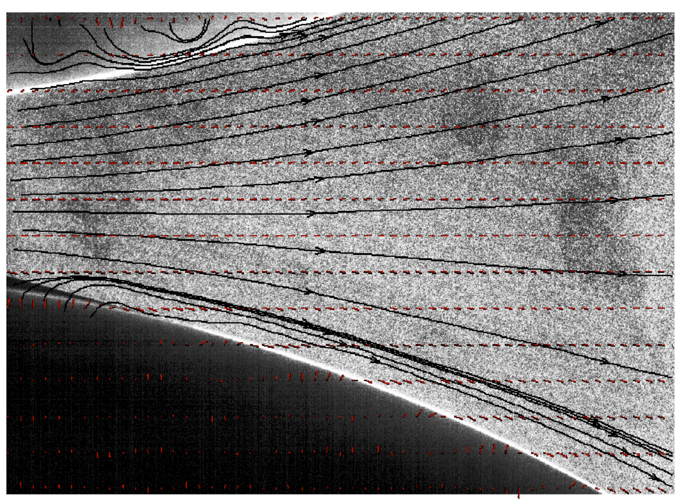
- Tire Spray Simulator or TSS completed (nearly)
- Demonstrated usefulness of TSS
  - Qualitative images using back-light and laser
  - Elucidate break-up mechanisms

Now the interesting (but hard) work begins

- Determine particles sizes and velocities


Instantaneous image


Vector field, average
of 1295 frames



Experiments on Spray from Tires

Improvements to apparatus needed

- Improve the water delivery
- Bring the experiment under computer control

Data acquisition

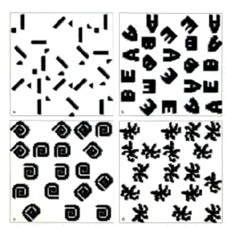
- Particle size distributions as a function of position in the field
- Velocity field, DPIV, for the various particle size categories

Requires local information on sizes (or scales)

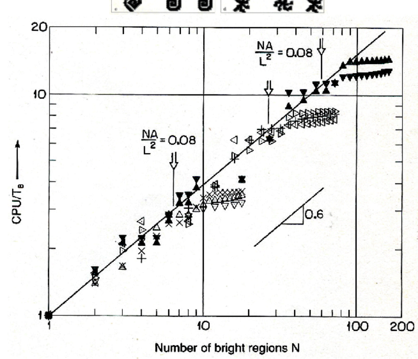
- Image segmenting (c.f., “An algorithm for rapid image segmenting”, Sinkewitsch & Browand, *Exp in Fluids*, (about 1985)
- Wavelet transform (c.f., “The growth of large scales at defect sites in the plane mixing layer”, Dallard & Browand *JFM* 1993)

Experiments on Spray from Tires

Image segmenting



Raster scan technique picks out complex-shaped particles.

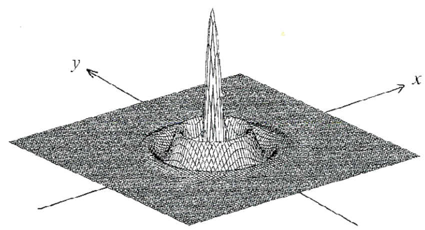


It is much faster than a sequential operation.

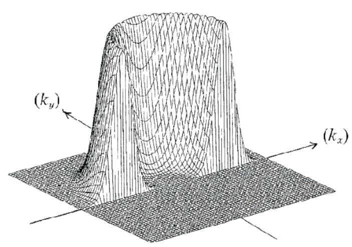
Experiments on Spray from Tires

Wavelet transform

Picks out spatial patterns, or scales, in space.



In wave number space, it is an arc, so we call it the Arc wavelet.



NRC·CNRC

From Discovery to Innovation...

NRC/NRCan Fuel Efficiency/Greenhouse Gas Program

J. Leuschen , K. R. Cooper

NRC Aerodynamics laboratory

Presented to DOE Heavy Vehicle Aerodynamics Meeting

May 12, 2005.

LLNL, Oakland, Ca.

Goals

- To save fuel and reduce greenhouse gas emissions in heavy-duty trucks
- To use fuel savings as catalyst for change
- To use aerodynamic technology to provide reductions
- To successfully transfer new technology to industry
  - Wind tunnel development
  - On-road testing and demonstration
- Involve the trucking industry through their Provincial and National organisations

Resources

- $800,000.00 Canadian dollars over FY 2004-2007
- Approximately $400,000.00 for model and full-scale wind tunnel testing
- The remainder for technology transfer, including:
  - Engineering road tests
  - Fleet trials
  - Seminars/web site/trade shows

Partners

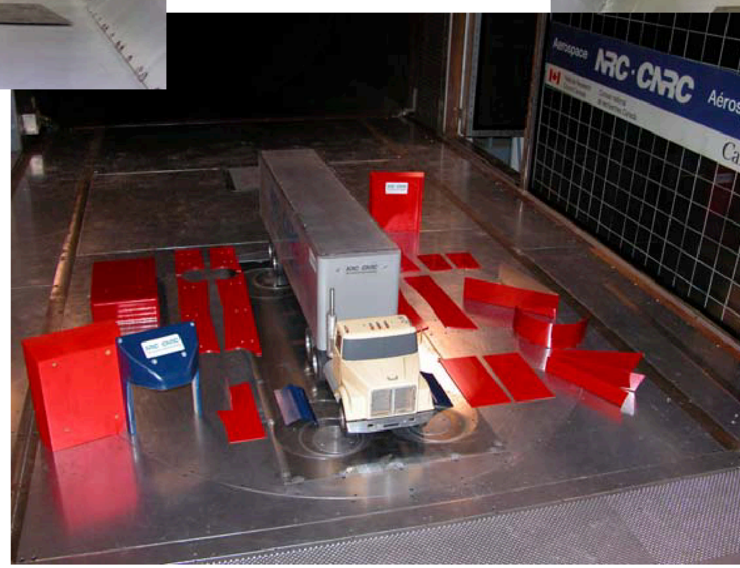
- ***Non-competitive, non-commercial program***
  - ***Not intended to invent products***
  - ***Designed to transfer technology to benefit of truckers & country***
- Funded by Natural Resources Canada
- Align effort with DOE program to lever investment
  - Test common hardware
  - Exchange wind tunnel and road data
  - Share hardware where possible
  - Interface with OEMs

Program Outline

- Model wind tunnel testing completed March 2005
- 1st-phase full-scale tunnel testing completed April 2005
- 2nd-phase full-scale tunnel testing in fall 2005
  - Need components for test
- Road and fleet trials 2006-2007
  - Need vehicles and hardware for test
    - Coast-down, fuel consumption
    - Fleet trials

Truck Fuel Saving Greenhouse Gas Reduction

Lets work together



NRC · CNRC

NRC·CNRC

From Discovery to Innovation...

Early Wind Tunnel Test Results from The NRC/NRCan Greenhouse Gas Program

J. Leuschen , K. R. Cooper

NRC Aerodynamics laboratory

Presented to DOE Heavy Vehicle Aerodynamics Meeting

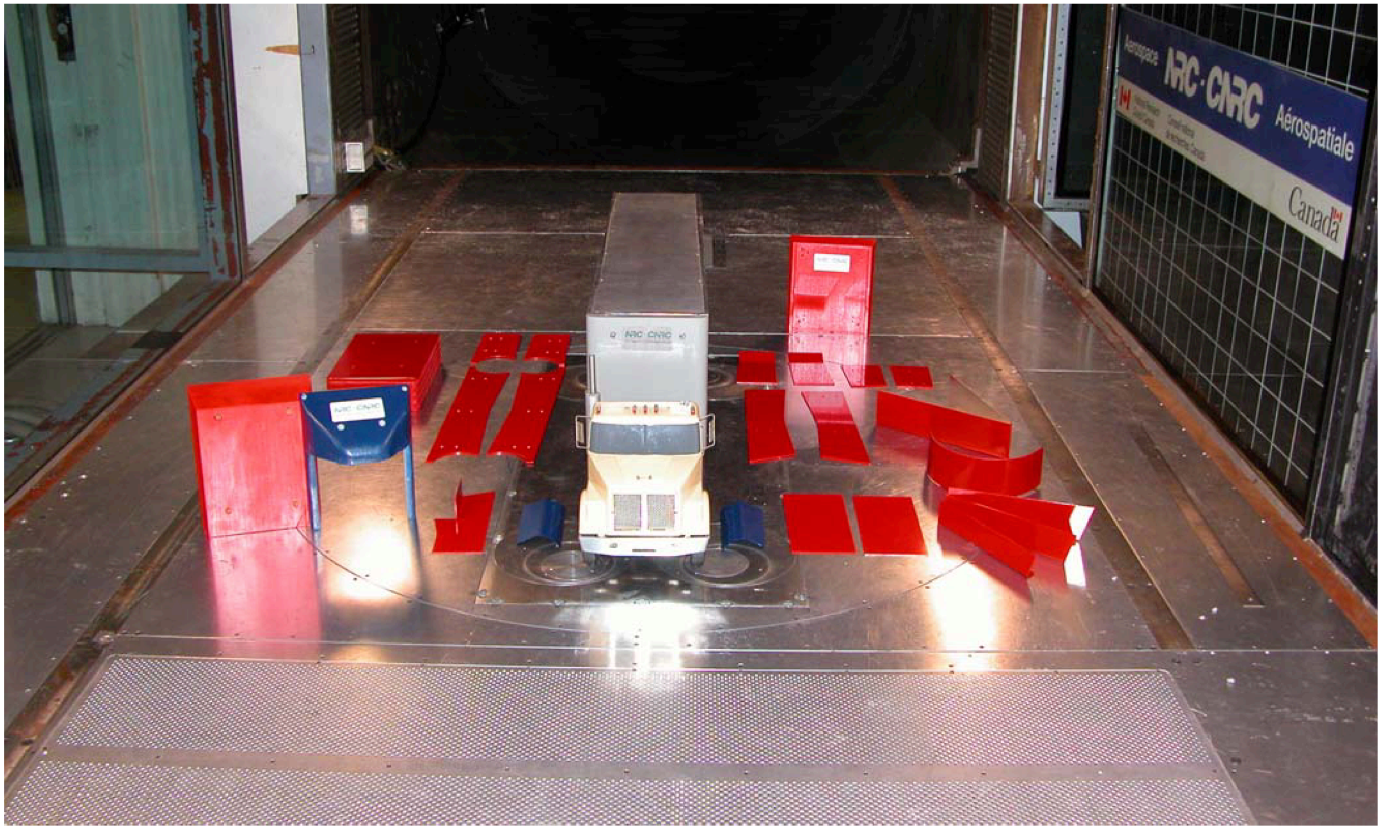
May 12, 2005.

LLNL, Oakland, Ca.

Model-Scale Development Program

- 1:10-scale highly detailed model
- Test speed of 75 m/s, $Re_W \approx 1.25 \times 10^6$
- Focussed on:
  - Boat-tail
  - Tractor/trailer gap treatments
  - Skirts
  - Under-trailer treatments

Model-Scale Development Program



Model-Scale Development Program

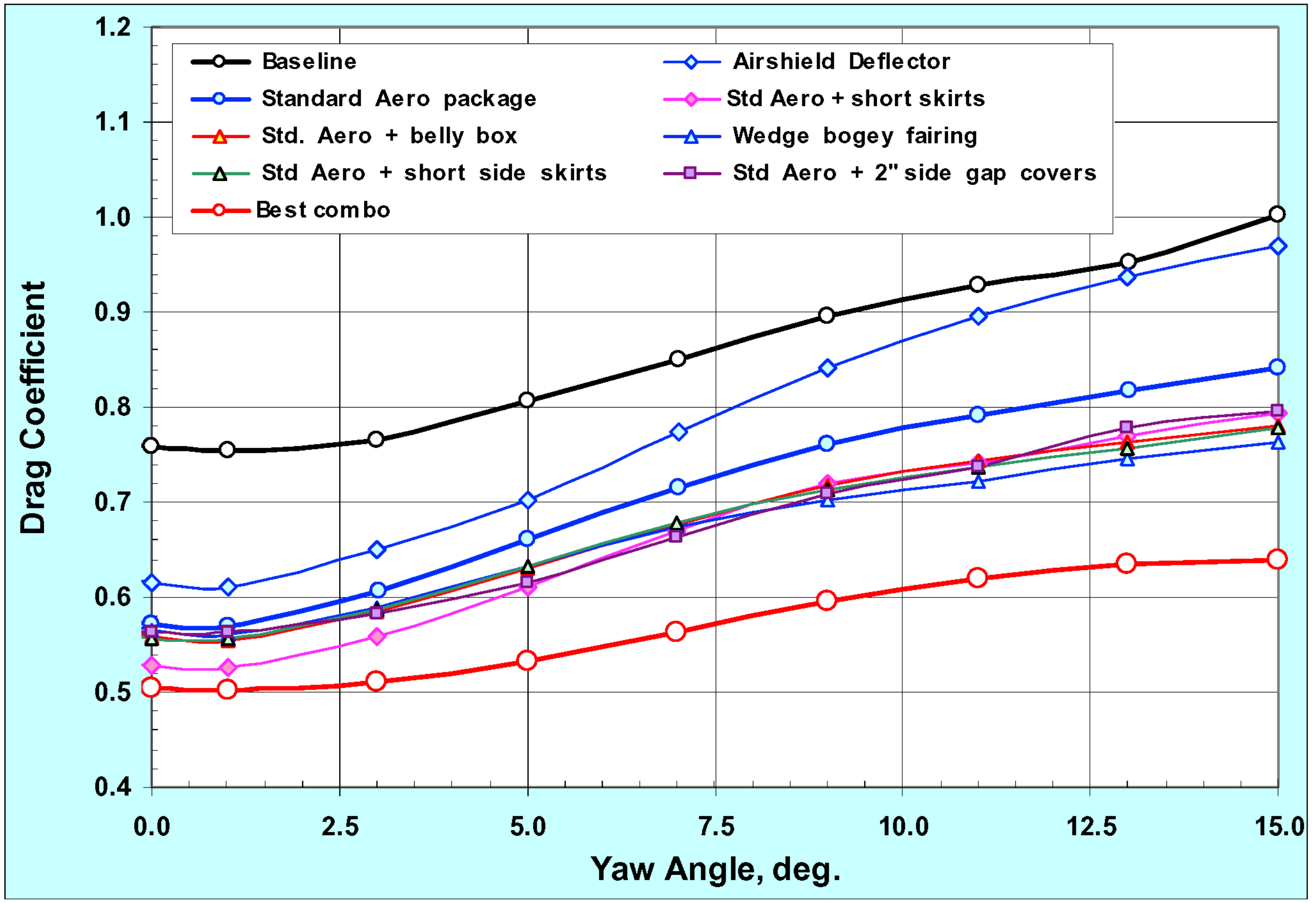
- Best combination – skirts, boat-tail, longer cab extenders

Model-Scale Development Program

Wedge bogie fairing | **Vortex stabilizer** | **Belly box**

NRC/NRCan Wind Tunnel Program

Summary of Model-Scale Results



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Summary of Model-Scale Results

Configuration	C_D bar 55 mph	C_D bar 65 mph	ΔC_D bar 55 mph	ΔC_D bar 65 mph	Fuel Savings [gal/100mi@65]
Std Aero Baseline	0.661	0.640	-	-	-
Std Aero + Boat-Tail	0.613	0.591	0.048	0.048	1.02
Std Aero + Long Skirts	0.618	0.601	0.043	0.038	0.81
Std Aero + Short Skirts	0.634	0.615	0.028	0.024	0.52
Std Aero + 2" Extenders	0.624	0.607	0.037	0.033	0.70
Std Aero + Belly box	0.631	0.613	0.030	0.027	0.57
Long Wedge Bogey Fairing	0.633	0.616	0.028	0.024	0.51
Best Combination	**0.540**	**0.529**	**0.121**	**0.111**	**2.35**

First Full-Scale Demonstration Program

- Full scale tractor and 40' trailer
- Test speed of 65 MPH
- Focussed on verifying best 1/10th scale configuration:
  - Boat-tail
  - Tractor/trailer gap treatments
  - Skirts

Full-Scale Best Combination

Full-Scale Test Items

Norcan Boat-Tail

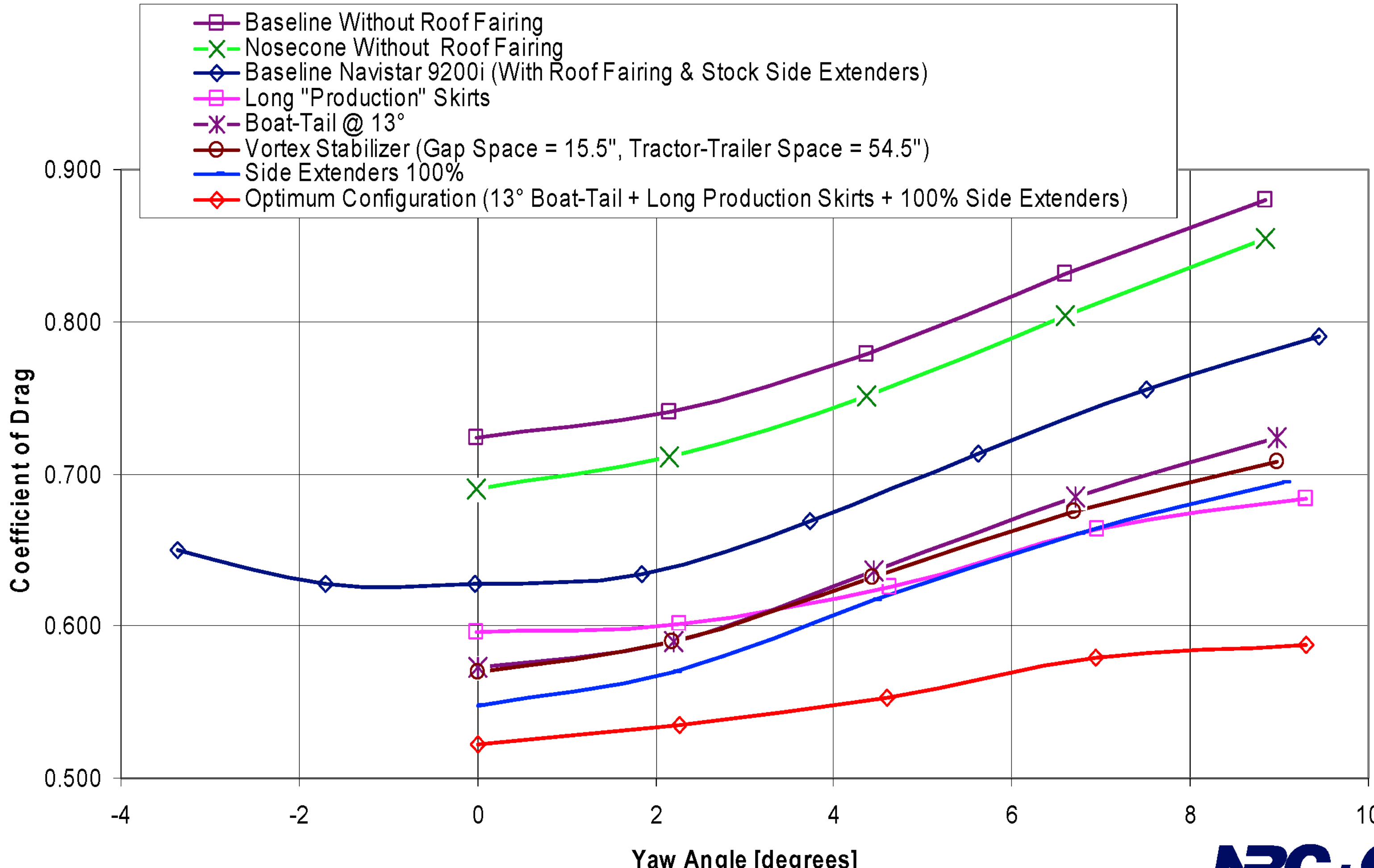
Side Extenders

Trailer Skirts

NRC · CNRC

NRC/NRCan Wind Tunnel Program

Summary of Full-Scale Results



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Summary of Full-Scale Results

Configuration	C_D bar 55 mph	C_D bar 65 mph	ΔC_D bar 55 mph	ΔC_D bar 65 mph	Fuel Savings gal/100mi@65
Non-Aero Baseline	0.812	0.791	-	-	-
Nosecone	0.784	0.762	0.029	0.029	0.62
Std Aero Baseline	0.716	0.695	0.096	0.097	2.05
Std Aero + Boat-Tail	0.662	0.643	0.054	0.052	1.10
Std Aero + Long Skirts	0.659	0.643	0.057	0.052	1.11
Std Aero + Side Extenders	0.640	0.621	0.077	0.073	1.56
Vortex Stabilizer	0.656	0.638	0.060	0.057	1.20
Best Combination	**0.580**	**0.567**	**0.136**	**0.128**	**2.71**

Conclusions

- Wind tunnel test allowed many prototype and production items to be tested quickly
- Most promising devices were skirts, boat-tails and side extenders
- Vortex stabilizer and underbody fairings aren't as effective
- While conclusions drawn from full- or 10th-scale data were similar, full-scale tests are felt to be more convincing

Follow-Up

- 2nd wind tunnel test in 2005 to test other prototypes (Freightwings, Aeroworks, Air Tabs?)
- CFD simulations to extrapolate results to other trailer configurations and lengths
- Fleet Trials / Outreach

Path Forward: A Summary

- Continue to improve computations
  - Pursue advanced meshing strategies
    - Embedded surfaces
  - Use higher fidelity geometries
    - Detailed underbody and engine compartment
  - More realistic environments
    - Rotating tires
    - Moving ground plane
- Looking at underhood thermal control
  - Using aircraft engines for design inspiration
    - Ducting the interior to partition the flow
    - Control the exit air
    - Propose an experimental program

Path Forward: A Summary

- Improving international cooperation
  - Canadian effort is driven by greenhouse gas emissions
  - Working to align effort with DOE programs
    - Test common hardware
    - Share data
    - Share hardware where possible
    - Combination of model and full-scale tests (road and wind tunnel)
    - Best drag improvement with skirts, base flaps, and side extenders
- Address operational issues
  - Need to work with fleets

Path Forward: A Summary

- Brake cooling and splash and spray: simulations
  - Ultimate goal is an integrated splay and spray model
  - Challenges need to be addressed
    - Complex geometries
    - Unsteady flow
    - Need models for droplet breakup and transport
    - Need validation data
  - Team advantages
    - Computational facilities
    - Expertise
- Splash and spray: experiments
  - Nearly completed work with the tire spray simulator
  - Examining the fundamental physics for jet breakup and droplet formation
  - Need to extract velocity fields and particle sizes
- Splash and spray leads to corrosion and icing